

WIND MEASUREMENTS WITH HIGH ENERGY 2 μ m COHERENT DOPPLER LIDAR

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ABSTRACT

A coherent Doppler lidar based on an injection-seeded Ho:Tm:YLF pulsed laser was developed for wind measurements. A transmitted pulse energy over 75 mJ at 5 Hz repetition rate has been demonstrated. Designs are presented on the laser, injection seeding, receiver, and signal processing subsystems. Sample data of atmospheric measurements are presented including a wind profile extending from the atmospheric boundary layer (ABL) to the free troposphere.

1. INTRODUCTION

Coherent lidars at 2- μ m wavelengths from holmium or thulium solid-state lasers have been extensively used to measure wind for applications in meteorology, aircraft wake vortex tracking, and turbulence detection.[1,2,3] These field-deployed lidars, however, have generally been of a pulse energy of a few millijoules, limiting their range capability or restricting operation to regions of high aerosol concentration such as the atmospheric boundary layer. Technology improvement in the form of high-energy pulsed lasers, low noise detectors, and high optical quality telescopes are being evaluated to make wind measurements to long ranges or low aerosol concentrations.

The Validar project was initiated to demonstrate a high pulse energy coherent Doppler lidar. Validar gets its name from the concept of “validation lidar,” in that it can serve as a calibration and validation source for future airborne and spaceborne lidar missions. Validar is housed within a mobile trailer for field measurements.

2. LIDAR SYSTEM DESIGN

A block diagram of the Validar instrument is shown in Figure 1 and a list of specifications is given in Table 1. The heart of the lidar is a diode-pumped pulsed Ho:Tm:YLF or Ho:Tm:LuLiF laser.

A holmium:thulium laser material was chosen for its 2- μ m wavelength that offers a high level of eye safety and pulse energy capability. This type of laser technology has shown a pulse energy as high as 600 mJ with a single-frequency spectrum.[4,5] The yttrium lithium fluoride host material has proven robust under strong pumping conditions with a low level of thermal lensing. However, recent laser research has suggested that the host material of lutetium lithium fluoride (LuLiF₄) can offer more output energy for the same pumping configuration.[6] The laser was recently converted to Ho:Tm:LuLiF, but the results described in section 3 are with Ho:Tm:YLF. The laser rod is side pumped by 6, conductively cooled, AlGaAs diode arrays; each array has six bars that can provide up to 600 mJ near 792 nm in a 1-ms pulse. Three sets of two diode arrays, side by side, are arranged 120° apart around the laser rod circumference. The laser rod has a diameter of 4 mm and is encased in a 6-mm outer-diameter fused-silica glass tube for water-cooling of the laser rod; the coolant temperature is kept at 15 C. The 20-mm long laser rod is doped with 6% Tm and 0.4% Ho. The resonator is in a ring configuration with a total length of 2.0 m, with an acousto-optic Q-switch to spoil the laser cavity.

A continuous wave Ho:Tm:YLF laser serves as both an injection seed source and local oscillator. This laser was originally built by Coherent Technologies, Inc. for the Space Readiness Coherent Lidar Experiment (SPARCLE).[7] Approximately 10 mW of this cw laser is split off and focused into a polarization maintaining optical fiber for the local oscillator channel. The rest of the cw power is used for injection seeding after being frequency shifted 105 MHz by an acousto-optic modulator. Such an offset sets an intermediate frequency between the local oscillator and pulsed laser output. To ensure a single-frequency pulsed output by the injection seeding process,

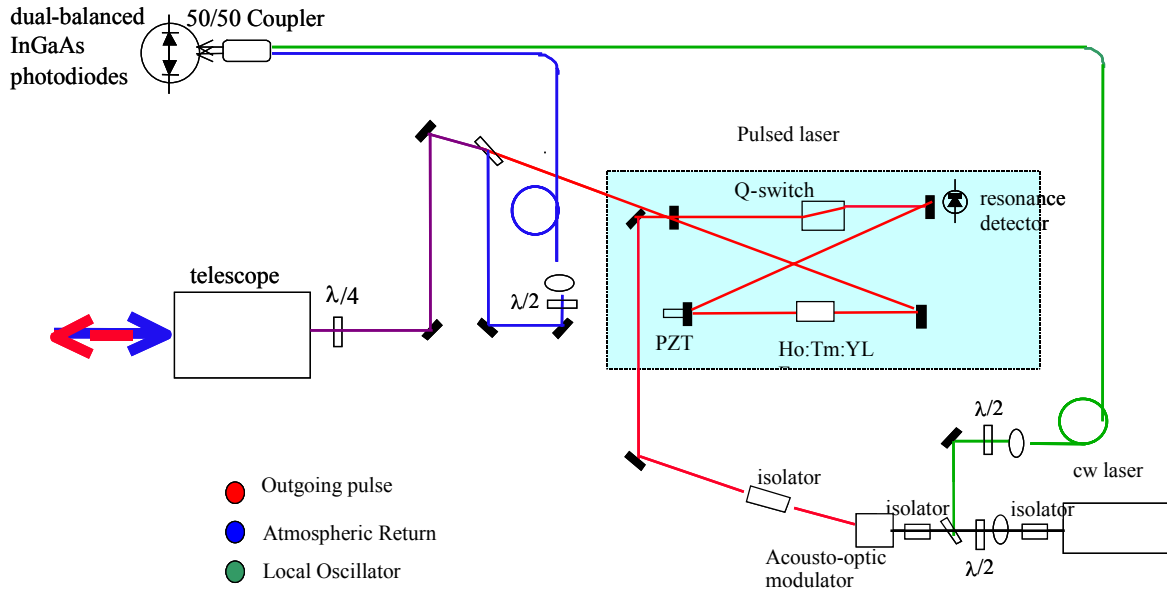


Fig. 1. Layout of the Validar optical system.

the pulse laser cavity is actively matched to the frequency of the injection seed by a ramp-and-fire technique.[8]

The pulsed laser output is transmitted to the atmosphere via a 4-inch diameter off-axis paraboloid telescope. After expansion by the telescope, the output laser beam can be pointed or scanned by a scanner

mounted through the roof of the trailer. The outgoing pulse and atmospheric backscatter are separated by a polarization relationship imposed by the combination of a quarter-wave plate and polarizing beam splitter. Heterodyne detection is provided by InGaAs photodiodes in a dual-balanced configuration. An advanced photodetector design is being used that combines the photodiode and transimpedance amplifiers (in die form) integrated together in the same microelectronic package. Such packaging lowers overall noise and lowers the parasitic capacitance of the various components for high bandwidth operation.

Processing of the lidar data is accomplished with a system diagrammed in Figure 2. The heterodyne signal is conditioned by an analog front end that includes an anti-aliasing filter and two different levels of amplification switched in to bring the outgoing scatter pulse and atmospheric return within the dynamic range of a digitizer. Digitized data then flows to an array of HammerHead digital signal processors for sectioning the lidar return into range bins, applying a spectral estimator, calculating Doppler shift, and averaging. These data products are tagged with time and azimuth/elevation angles at which the laser beam is pointing before being sent to algorithms for displaying wind fields.

Table 1: Specifications of Validar

| | Reported configuration* Ho:Tm:YLF | Upgraded configuration Ho:Tm:LuLiF |
|------------------------|---|--|
| Laser material: | | |
| Pulse energy: | >75mJ | 95mJ |
| Wavelength: | 2050.8nm | 2053.5 nm |
| Pulse width: | 150ns | 140 ns |
| Pulse repetition rate: | 5-10Hz | 5-10 Hz |
| Spectrum: | Single frequency | Single frequency |
| Beam quality: | < 1.3 x diffraction limit | < 1.3 x diffraction limit |
| Telescope dia.: | 4 inch | 6 inch |
| Scanner: | full hemispheric 20 cm dia. aperture | full hemispheric 20 cm dia. aperture |
| Digitization rate: | 500 Ms/s, 8 bits | 500 Ms/s, 8 bits |

*NOTE: Data presented in this paper were acquired using this configuration

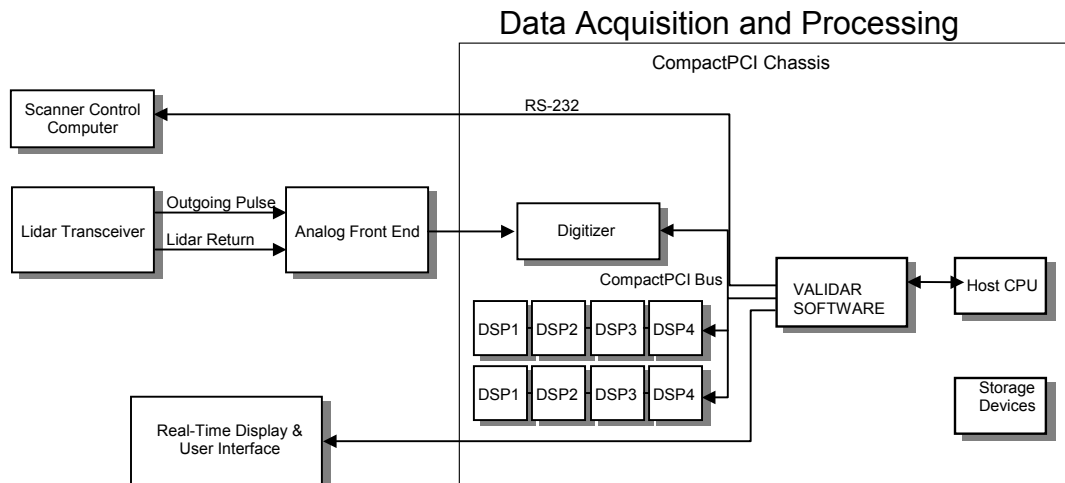


Fig. 2. Layout of the Validar electronics and real-time processing system.

3. WIND DATA

The wind data discussed in this section was acquired with a Ho:YLF laser producing 75 mJ and with a 4-inch aperture telescope. The real-time processing system is capable of acquiring and

3 different directions. The first 2 are orthogonal wind profile measurements at an elevation angle of 45 degrees, from which the horizontal wind profile is measured. Figure 3, shows an example of a wind profile up to an altitude of 8 km. In this profile the top

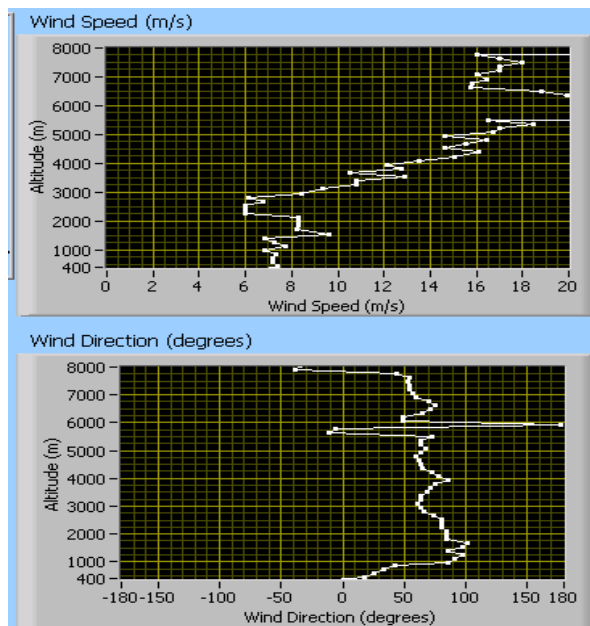


Fig. 3. Horizontal wind profile.

processing lidar wind profile data at a laser repetition rate of 10 Hz. In the day-to-day operation of Validar a rate of 5 Hz is used to maximize laser diode lifetime. Wind data are acquired by pointing the lidar scanner in

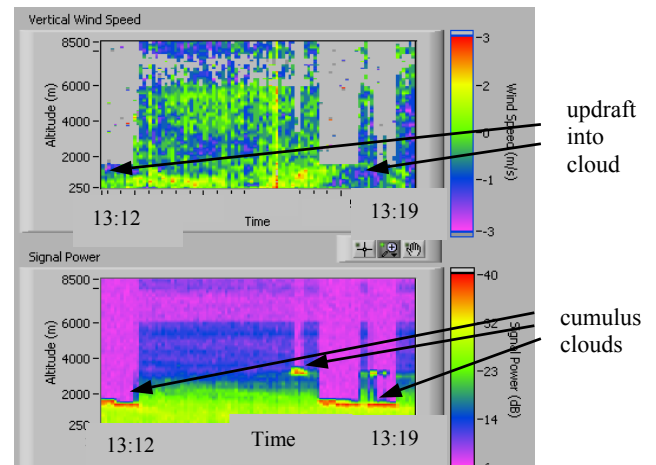


Fig. 4. Vertical wind speed time history.

of the atmospheric boundary layer can be seen at 2800 m and is marked by a sharp increase in the wind speed. The erratic results between 5600 m to 6500 m are due to the loss of signal resulting from very low aerosol levels. The signal returns above 6500 m as a result of encountering cloud cover. The third scanner position is pointing at zenith to measure the vertical wind speed. Figure 4, is a time history of vertical wind speed measurements taken over a 7-minute time span. The upper plot is wind speed versus altitude and the lower

plot is signal power versus altitude. The plots show the passing of cumulus cloud cover, which result in the total attenuation of the lidar pulse in the cloud. It can be seen in these data that during the presence of a cloud updrafts into the clouds were measured on the order of 1 – 2 m/s. While a downdraft of about 1 – 2 m/s were observed during the absence of cloud cover. Figure 5 shows a vertical wind speed time history that was taken on a clear day. These data illustrate Validar's capability to measure wind speeds above the atmospheric boundary layer. It can be seen that the top of the ABL is at 2500 m, while vertical wind speeds were measured up to 5000 m. Also, sub-visible cirrus clouds were detected at 12000 m. This cirrus cloud

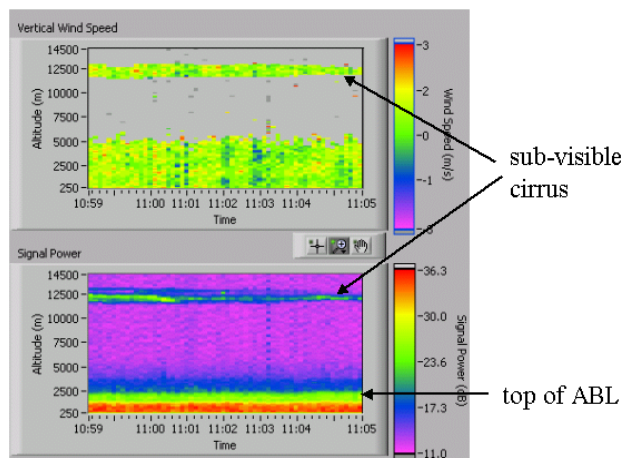


Fig. 5. Clear sky vertical wind speed time history.

layer yielded sufficient signal strength to produce wind measurements in the upper reaches of the troposphere. Measurements have also been made during periods of rain with the measured speed of the rain being 9 - 11 m/s, which is in good agreement with the terminal velocity of rain.

REFERENCES

1. S.M. Hannon, S.W. Henderson, J.A. Thomson, and P. Gatt, "Autonomous lidar wind field sensor: performance predictions," *SPIE*, Volume 2832, pp. 76-91, 1996.
2. C.J. Grund, R.M. Banta, J.L. George, J.N. Howell, M.J. Post, R.A. Richter, A.M. Weickmann, "High-Resolution Doppler Lidar for Boundary Layer and Cloud Research," *J. Atmos. And Ocean. Tech*, 18, 376-393 (2001)
3. P. Brockman, B.C. Barker, G.J. Koch, D.P.C. Nguyen, and C.L. Britt, "Coherent pulsed lidar sensing of wake vortex position and strength, winds and turbulence in airport terminal areas," *Tenth Biennial Coherent Laser Radar Technologies and Applications Conference*, pp. 12-15 (1999).
4. U.N. Singh, J. Yu, M. Petros, N.P. Barnes, J.A. Williams-Byrd, G.E. Lockard, and E.A. Modlin, "Injection-seeded, room-temperature, diode-pumped Ho:Tm:YLF laser with output energy of 600 mJ at 10 Hz," in *Advanced Solid-State Lasers*, Vol. 19 of *OSA Trends in Optics and Photonics*, pp. 194-196 (1998).
5. J. Yu, A. Braud, S. Chen, M. Petros, and U.N. Singh, "High Energy Double Pulsed Ho:Tm:YLF Laser Amplifier," paper SP2.13, *21st International Laser Radar Conference* (2002).
6. M. Petros, J. Yu, S. Chen, U.N. Singh, B.M. Walsh, Y. Bai, and N.P. Barnes, "High energy diode pumped Ho:Tm:LuLiF₄ laser for lidar applications," *SPIE's Third International Asia-Pacific Environmental Remote Sensing Symposium 2002: Remote Sensing of the Atmosphere, Ocean, Environment, and Space*, Hangzhou, China, October 2002
7. M.J. Kavaya and G.D Emmitt, "The Space Readiness Coherent Lidar Experiment (SPARCLE)," paper 3380-03, *Proc. SPIE* Vol. 3380, pp. 2-11, *Aerosense Conference*, Orlando, FL (1998).
8. S.W. Henderson, E.Y. Yuen, and E.S. Fry, "Fast resonance detection technique for single-frequency operation of injection seeded Nd:YAG lasers," *Opt. Lett.* 11, 715-717 (1986).